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Sensitivity of Pion versus Parton-Jet Nuclear Modification Factors to the Path-Length Dependence of Jet-Energy Loss at RHIC and LHC

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Abstract. We compare the jet-path length and beam-energy dependence of the pion nuclear modification factor and a parton-jet nuclear modification factor at RHIC and LHC. We contrast predictions based on a linear pQCD and a highly non-linear hybrid-AdS holographic model of jet-energy loss. We find that both models require a reduction of the jet-medium coupling from RHIC to LHC to account for the measured pion nuclear modification factor. In case of the parton-jet nuclear modification factor, however, which serves as a lower bound for the LO jet nuclear modification factor of reconstructed jets, the extracted data can be characterized without a reduced jet-medium coupling at LHC energies. We conclude that while reconstructed jets are sensitive to both quarks and gluons and thus provide more information than the pion nuclear modification factor, their information regarding the jet-medium coupling is limited due to the superimposition with NLO and medium effects. Hence, a detailed description of the underlying physics requires both the leading hadron and the reconstructed jet nuclear modification factor. Unfortunately, the results for both the pion and the parton-jet nuclear modification factor are insensitive to the jet-path dependence of the models considered.

PACS. 12.38.Mh Quark-gluon plasma – 25.75.Bh Hard scatterings in relativistic heavy-ion collisions – 11.25.Tq Gauge/string duality

1 Introduction

Jet-quenching observables have proven to render important information about the evolution of the quark-gluon plasma (QGP) created in heavy-ion collisions [1,2]. It got evident that *both* the jet-medium dynamics and the bulk medium evolution influence the jet-quenching observables [3,4,5,6,7,8,9]. However, it remains a formidable task to identify the details of the jet-medium interactions and the jet-energy loss formalism.

While it was shown that the "surprising transparency" of the medium created at the LHC [5,6,10,11] can be described by perturbative QCD (pQCD) processes including a running of the jet-medium coupling [4,5,6,7,8,9,10,11, 12,13,14,15,16,17], it remains an open question if pQCD is the correct prescriptions for the jet-energy loss at RHIC and LHC or if string theory based on the AdS/CFT correspondence [18,19,20,21] with strings shooting up or falling into black holes must be applied.

A main difference between pQCD and AdS/CFT calculations of the jet-energy loss is the path-length dependence [3,4,7]. Commonly, it is assumed that there is a linear path-length dependence ($dE/dx \sim x^{z=1}$) for pQCD processes and a squared path-length dependence ($dE/dx \sim x^{z=2}$) for AdS/CFT-based scenarios.

Recently, we performed a systematic study on the jet-energy loss [4] based on a generic energy loss model [4,10] that can interpolate between a pQCD and an AdS/CFT jet-energy loss prescription. We demonstrated that we cannot constrain the path-length dependence narrower than $z = [0, 2]$. In particular, we showed that the rapid rise of the pion nuclear modification factor R_{AA} at LHC energies disfavors a *conformal* AdS/CFT prescription (with the same jet-medium coupling at RHIC and LHC). *Non-conformal* AdS/CFT, however, with a jet-medium coupling reduced at LHC energies describes the measured pion data [3,22,23,24].

Last year, Casalderrey-Solana et al. introduced a "hybrid strong/weak approach" [18] based on the idea that any parton of a jet propagating through a quark-gluon plasma suffers hard splitting, while additionally each of these partons possesses soft fields that interact strongly with the medium. The jet-energy loss prescription in Ref. [18] is based on strings falling into black holes featuring a non-linear Bragg peak [19]. Casalderrey-Solana et al. showed that their ansatz reproduces the experimentally determined Jet R_{AA} for reconstructed jets at LHC energies and renders a Jet R_{AA} at RHIC energies that is very similar to the measured pion nuclear modification factor

for *the same coupling* as considered for LHC energies, suggesting that the hybrid strong/weak approach including the Bragg peak favors a conformal AdS/CFT prescription. In the following, we will refer to this energy-loss ansatz as Hybrid AdS.

In this paper, we determine the jet-energy loss based on radiative pQCD [4,10] and on the Hybrid AdS energy-loss ansatz of Ref. [18]. We compare the pion nuclear modification factor with a parton-jet nuclear modification factor that can be considered as an idealized LO Jet R_{AA} at RHIC and LHC energies. For both scenarios, the measured pion nuclear modification factor can only be described if a reduced jet-medium coupling at LHC energies is considered. In case of the Jet R_{AA}, however, our results suggest as in Ref. [18] that the measured Jet R_{AA} can possibly be characterized without a reduced jet-medium coupling at LHC energies.

We conclude that the information of reconstructed jets regarding the jet-medium coupling is limited and superimposed by NLO/medium effects. While reconstructed jets do certainly provide more information regarding the quark and gluon contributions, the information on the jet-medium coupling cannot be extracted unambiguously. To do so, a leading hadron nuclear modification factor is needed. Besides that, the study shows that the Hybrid AdS energy-loss approach also favors a *non-conformal* approach as the measured pion nuclear modification factor can only be described with a reduced jet-medium coupling at LHC energies. We demonstrate that neither the pion nor the Jet R_{AA} are sensitive to the path-length difference between the pQCD and the Hybrid AdS energy-loss model. Thus, we confirm that the path-length dependence for a jet-energy loss in heavy-ion collisions cannot be constrained further than $z=[0,2]$ [4].

2 The jet-energy loss models

2.1 The generic energy-loss model

The jet-energy loss prescription for the pQCD process considered is based on our generic jet-energy loss model [4, 10] that parametrizes the energy loss via

$$\frac{dE}{dx}=\frac{dE}{d\tau}=-\kappa(T)E^a(\tau)\,\tau^z\,T^{c=2+z-a}\,\zeta_q\,. \qquad (1)$$

Here, the jet-energy dependence, the path-length dependence, the temperature dependence, and the jet-energy loss fluctuations are characterized by the exponents (a, z, c, q). The jet-energy loss fluctuations are distributed via $f_q(\zeta_q)=\frac{(1+q)}{(q+2)^{1+q}}(q+2-\zeta_q)^q$, allowing for an easy interpolation between non-fluctuating ($q=-1$, $\zeta_{-1}=1$), uniform Dirac distributions and distributions increasingly skewed towards small $\zeta_q<1$ for $q>-1$.

The jet-medium coupling is $\kappa(T)=C_r\kappa'(T)$ for quark ($C_r=1$) and gluon ($C_r=\frac{C_A}{C_F}=\frac{9}{4}$) jets. Those jets are distributed according to a transverse initial profile specified by the bulk QGP flow fields given by the transverse plus Bjorken (2+1)d expansion of VISH2+1 [25].

While this model can in principal be used to study a string-like jet-energy loss [4,10], we strictly limit our discussion here to a radiative pQCD scenario including jet-energy loss fluctuations specified by ($a=0, z=1, c=3, q=0$). This setting describes the data measured at RHIC and LHC very well [4].

2.2 The Hybrid Strong/Weak Approach

The jet-energy loss of the "hybrid strong/weak approach" [18] is based on the falling string prescription by Chesler et al. [19]

$$\frac{1}{E_{\rm in}}\frac{dE}{dx}=-\frac{4}{\pi}\frac{x^2}{x^2_{\rm stop}}\frac{1}{\sqrt{x^2_{\rm stop}-x^2}}\,, \qquad (2)$$

featuring a Bragg peak. Here, the initial jet energy is E_{in}. The string stopping distance for quark and gluon jets is given by

$$x^{q,g}_{\rm stop}=\frac{1}{2\kappa^{(g)}_{\rm sc}}\frac{E^{1/3}_{\rm in}}{T^{4/3}} \qquad (3)$$

and the jet-medium coupling for gluon jets reads $\kappa^{(g)}_{\rm sc}=\kappa_{\rm sc}\left(\frac{C_A}{C_F}\right)^{1/3}$, including the Casimir operators C_A and C_F. This energy-loss ansatz is integrated into our existing model [4,10]. As for the pQCD scenario, we consider the (2+1)d viscous hydrodynamic bulk evolution of VISH2+1 [25] as background, averaging over all possible initial energies E_{in}.

2.3 Model comparison

In Ref. [4], we considered an AdS/CFT inspired scenario with $\frac{dE}{d\tau}=-\kappa(T)E^0(\tau)\,\tau^2\,T^4\,\zeta_q$. The main difference between this ansatz and Eq. (2) is the square-root dependence describing the Bragg peak with the explosive burst of energy close to the end of the jet's evolution.

There have been extensive discussions in literature [18, 20,26] on the impact of the Bragg peak, however, we are going to show below that the difference of an AdS energy-loss model featuring a Bragg peak to a pQCD model without a Bragg peak [4,5,6,8,9,10,26] is only marginal.

2.4 Pion and Jet R_{AA}

As in Refs. [4,10] we use the KKP pion fragmentation functions [27] that have successfully been tested on the $pp\to\pi^0$ spectra at RHIC and LHC [28] to determine the pion nuclear modification factors.

In contrast to Ref. [18], however, we do not reconstruct jets with FASTJet [29] but use the ansatz that

$$\text{Jet } R_{AA}=\frac{R^g_{AA}\,d\sigma_g(p_T)+R^q_{AA}\,d\sigma_q(p_T)}{d\sigma_g(p_T)+d\sigma_q(p_T)} \qquad (4)$$

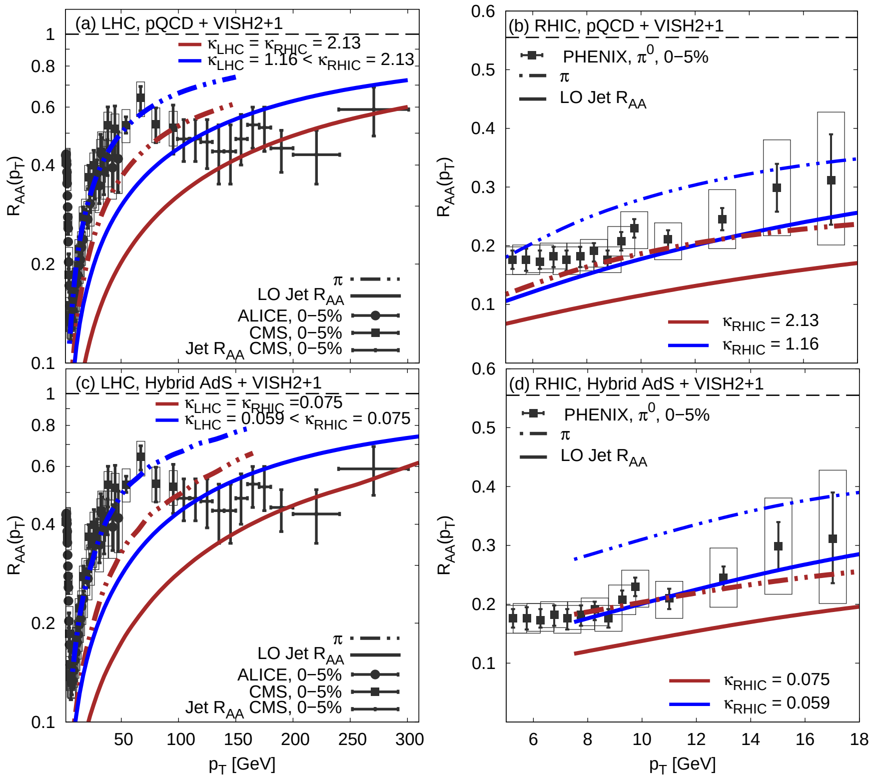

Fig. 1. (Color online) The pion nuclear modification factor (dashed-dotted lines) and the LO Jet R_{AA} (solid lines) calculated via the radiative pQCD-like energy-loss ansatz given by Eq. (1) with $(a = 0, z = 1, c = 3, q = 0)$ (upper panel) and the hybrid strong/weak string energy-loss ansatz given by Eq. (2) (lower panel) at LHC (left) and RHIC (right) energies for larger (red) and lower (blue) jet-medium couplings compared to the measured data [3,22,23,24].

and the pQCD cross-sections from WHDG [17] to obtain an idealized LO Jet R_{AA}. Naturally, this LO Jet R_{AA} is only a lower bound for the NLO Jet R_{AA} with jet-cone radii $R > 0$. For a detailed discussion on the NLO and medium effects, please cf. to Ref. [30].

3 Results of the model comparison

Figure 1 shows the nuclear modification factor for pions (dashed-dotted lines) and for the Jet R_{AA} (solid lines) calculated via the pQCD jet-energy loss ansatz of Eq. (1) (upper panel) and the hybrid strong/weak string energy loss given by Eq. (2) (lower panel) at LHC (left) and RHIC (right) energies for two different jet-medium couplings, a larger one (red) and a lower one (blue), compared to the data from PHENIX, ALICE, and CMS [3,22,23,24].

The solid blue lines for the Jet R_{AA} in the left panels of Fig. 1 describe the experimental data extracted for the Jet R_{AA} at LHC energies within the present error bars for a jet-medium coupling of $\kappa = 1.16$ (pQCD, upper panel) and $\kappa = 0.059$ (Hybrid AdS, lower panel), respectively. Fragmenting this result to obtain the pion nuclear modification factor (dashed-dotted lines) leads to an R_{AA} that reproduces the measured pion nuclear modification factor at LHC as well. Please note that the yield of this pion nuclear modification factor is enhanced over the Jet R_{AA} for the same jet-medium coupling which will be discussed below.

A straight extrapolation of this results to RHIC energies (right panels of Fig. 1), however, shows that the Jet R_{AA} for *the same* jet medium couplings of $\kappa = 1.16$ (pQCD) or $\kappa = 0.059$ (Hybrid AdS) (solid blue lines) by pure chance lie on top of the measured *pion* nuclear modification factor. Fragmenting this result to pions leads to a R^{π}_{AA} that is larger than the measured data at RHIC.

For larger jet-medium couplings of $\kappa = 2.13$ (pQCD) and $\kappa = 0.075$ (Hybrid AdS) (red lines), however, the *pion* nuclear modification factor at RHIC is described (dashed-dotted red lines) but underpredicts the pion nuclear modification factor at the LHC, as known from the "surprising transparency" at the LHC [6]. On the other hand, the Jet R_{AA} for this scenario also describes the extracted data from ALICE and CMS within the present error bars.

Of course, this idealized LO Jet R_{AA} is only a lower bound for the reconstructed nuclear modification factor and thus a Jet R_{AA} extracted from reconstruction algorithms will show a larger yield.

Please note that for this comparison, the jet-medium coupling has been treated as a constant. However, most recently [5] it has been shown that the jet-medium coupling is not a constant but depends on the energy of the jet and the temperature of the medium.

Thus, in the large-p_T range there are several competing effects:

1. a jet-medium coupling depending on the jet-energy and the temperature of the medium,
2. NLO and medium effects [30], and
3. the jet-cone size R enhancing the R_{AA} for larger R.

The extracted data suggest that these effects act in opposite directions tending to cancel out at the end and leading to a $R^{\pi}_{AA} \sim \mathrm{Jet}R_{AA}$, limiting the information of the reconstructed jets regarding the jet-medium coupling.

Besides that, Fig. 1 shows that the results for the pQCD and the Hybrid AdS energy-loss including a Bragg peak are remarkably similar. Thus, neither the pion nor the Jet R_{AA} are sensitive to the difference in the path-length between pQCD and AdS models.

4 Summary

We compared the pion nuclear modification factor and a parton-jet nuclear modification factor describing the LO Jet R_{AA} at RHIC and LHC energies for a jet-energy loss based on radiative pQCD [4,10] and on a hybrid strong/weak approach for falling strings [18]. We found that for both scenarios the measured pion nuclear modification factor can only be described considering a reduced jet-medium coupling at the LHC, while in case of the Jet R_{AA} the experimental data can be characterized with the same jet-medium coupling at RHIC and LHC as discussed in Ref. [18].

For the Jet R_{AA}, however, there are several different competing effects: (1) a jet-medium coupling depending on the jet energy and the temperature of the medium [5], (2) NLO and medium effects [30], as well as (3) the impact of the jet cone radii R increasing the Jet R_{AA} for larger values of R [30]. These effects tend to cancel each other, resulting in a $R^{\pi}_{AA} \sim \mathrm{Jet}R_{AA}$.

Altogether, these findings confirm our results of Ref. [4]. Both, a pQCD-based jet-energy loss and a non-conformal AdS/CFT-based approach can describe the present experimental data. Besides that, the results based on the pQCD and the AdS approach are insensitive to the jet-path length dependence of the models considered. Consequently, the path-length dependence for the jet-energy loss in heavy-ion collisions cannot be constrained further than $z = [0, 2]$.

We conclude that while reconstructed jets are sensitive to both quarks and gluons and thus provide more information than the pion nuclear modification factor, their information on the jet-medium coupling is limited due to the superposition with NLO and medium effects as well as the impact of the jet cone radii. Therefore, a complete description of the underlying jet physics requires to study both the leading hadron nuclear modification factor and the reconstructed jet nuclear modification factor.

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